

M.O.637

HANDBOOK
OF
WEATHER FORECASTING

METEOROLOGICAL OFFICE

1964

U.D.C.
551.509.3(02)

PREFACE

The Handbook of Weather Forecasting was written mainly for distribution within the Meteorological Office to provide forecasters with a comprehensive and up-to-date reference book on techniques of forecasting and closely related aspects of meteorology. The work, which appeared originally as twenty separate chapters, is now re-issued in three volumes in loose-leaf form to facilitate revision.

Certain amendments of an essential nature have been incorporated in this edition but, in some chapters, temperature values still appear in degrees Fahrenheit. These will be changed to degrees Celsius when the chapters concerned are completely revised.

CHAPTER 20
BUMPINESS IN AIRCRAFT

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CHAPTER 20

BUMPINESS IN AIRCRAFT

20.1. INTRODUCTION

Bumpiness in aircraft is a familiar phenomenon to pilots and others who fly regularly. To passengers, bumpiness is a cause of discomfort and inconvenience and very occasionally, if severe bumpiness sets in without warning at a time when seat straps are not fastened, injuries amongst the passengers may occur. Some passengers find bumpiness acutely unpleasant and having once experienced a particularly rough flight will avoid flying whenever possible. The subject is therefore of concern to airline operators who naturally wish to avoid discouraging the growth of air travel. To pilots, bumpiness is a factor which makes their task more difficult and in severe cases may endanger the safety of their aircraft. The aircraft designer is also involved as he must make due allowance for the cumulative effect of the stresses imposed on the aircraft by turbulence, as well as for the maximum stress likely to arise from any individual gust.

Bumpiness experienced in aircraft is merely a manifestation of turbulence in the atmosphere. However, turbulence is a problem of which our knowledge and understanding are far from complete and many of the questions which arise for the pilot, airline operator and aircraft designer cannot yet be answered satisfactorily. In particular, turbulence is one of the most difficult phenomena to forecast with any precision.

It is well known that the atmosphere rarely flows in a smooth steady fashion. More usually the wind is subject to fluctuations of a largely random character and the flow is then said to be turbulent. Typical flow in nature can be regarded as a smooth basic flow on which are superimposed the fluctuations giving rise to turbulence. This leads to the conception of an "eddy", a term which cannot be precisely defined, but which is used to describe an irregularity in a flow. An eddy does not necessarily have the character of a whirl or vortex although motions of such a type are often involved. The eddy is merely an irregularity or turbulent entity of unspecified character.

In typical turbulent flow in the atmosphere eddies of a widely varying range of sizes are present with the turbulent energy continually passing from the larger to the smaller eddies and being ultimately dissipated by viscous forces. In passing through turbulent air an aircraft acts selectively in its response to the eddies so that its behaviour is a function of the size, speed, and aerodynamic characteristics of the aircraft as well as of the character of the turbulence.

For our present purpose we may classify turbulence into three main types namely, mechanical, thermal and clear air. In the layers near the ground the smooth flow of wind is disrupted by vegetation, trees, buildings and topographical irregularities, all of which give rise to eddies of various sizes. Turbulence arising in this way is commonplace and is appropriately called mechanical turbulence. The turbulence caused by free convection, when buoyant bubbles or columns rise through the atmosphere, is known as thermal turbulence. Generally the eddies involved in thermal turbulence are larger than in mechanical turbulence and this affects the frequency with which an aircraft encounters individual bumps. Very often, of course, mechanical and thermal turbulence operate simultaneously. These two forms of turbulence are understandable, at least superficially, because they are intuitively plausible. Clear-air turbulence, however, is more difficult

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because it is not the direct outcome of mechanical obstructions or of buoyant convection. Indeed, although wind shear is known to be an important factor, the precise mechanism of clear-air turbulence is yet to be established. As we shall see in Section 20.2, it is largely a phenomenon of the upper troposphere.

20.2. SOURCES OF TURBULENCE RELEVANT FOR AVIATION

20.2.1. *Turbulence in the friction layer*

The friction layer varies widely in vertical extent from time to time and place to place, its depth being determined partly by meteorological factors and partly by the nature of the terrain. Typically the depth of the friction layer may range from a few hundred feet up to perhaps 3000 feet or so. Within this layer, the smooth flow of the atmosphere is disrupted by disturbances arising directly from the irregularities at the earth's surface — trees, buildings, hills and other terrain features, etc. The effect of this roughness is to cause eddies or fluctuations over a wide range of scales to be imparted to the flow of wind, these eddies being responsible for the familiar gusts and lulls to which the surface wind is always subject. The gusts may be from any direction although close to the surface there is naturally a tendency for downward gusts to be inhibited by the proximity of the surface itself. Farther removed from the surface, vertical gusts in either direction are able to develop more readily. Thus on a typical day with mechanical turbulence operating in the friction layer, the picture is one of predominantly horizontal gusts and lulls near the ground, with the gusts becoming more random in direction as one proceeds upwards in the friction layer. Gusts from any direction may give rise to bumpiness in an aircraft, although as we shall see later a vertical gust of a given speed affects an aircraft to a greater extent than a horizontal gust of the same speed.

Purely mechanical turbulence is a feature of airstreams in which there is an absence of heating, for example on non-convective cloudy days and at night. It is characterized by a continual sequence of rapid fluctuations having a dominant period of a few seconds only. Thermal turbulence on the other hand arises in conditions of steep lapse rate and is a manifestation of free convection due to buoyancy. The eddies from purely thermal turbulence are much larger than those produced by direct mechanical effects so that at any one place they occur less frequently. Indeed the period of thermal eddies may sometimes be one to two orders of magnitude longer than that of mechanically produced eddies. Nevertheless the transition zone on entry into a thermal up-current is commonly a region where sudden short-period gusts are experienced. Thermal turbulence predominates on occasions with light winds and free convection, for example on a quiet, warm, sunny afternoon, whereas mechanical turbulence is most in evidence on a windy day without heating.

These two kinds of turbulence within the friction layer give rise to characteristic kinds of bumpiness in an aircraft. Mechanical turbulence causes frequent jolts not unlike those felt in a vehicle travelling over a very bumpy road; thermals, however, although they may also cause sudden jolts, are more often associated with accelerations which are sustained over many seconds and produce effects more akin to those experienced in a rapidly accelerating lift. The two kinds of turbulence also produce characteristic fluctuations of surface wind

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and may often readily be distinguished from an examination of anemograph traces — see for example the anemograms reproduced as Figure 13 of Chapter 13 (Wind). Very often the two kinds of turbulence operate simultaneously.

The factors of importance in determining the intensity of turbulence within the friction layer are:

- (i) wind strength,
- (ii) terrain roughness,
- and (iii) lapse rate.

For the generation of mechanical turbulence the relevance of wind strength and terrain roughness is obvious. In general, bumpiness of significance to aircraft requires surface winds of about 15 knots upwards. Given sufficiently strong winds, the intensity of mechanical turbulence depends on the roughness of the terrain. More powerful eddies, able to impart more severe bumps to an aircraft, are generated over country which is rugged, irregular and hilly than over a flat smooth plain devoid of obstructions. This is strikingly borne out by flight across a coastline from sea to land at low level. All regular air travellers are familiar with the abrupt onset of bumpiness at the coast in these circumstances, even when thermal effects are absent. The decrease in turbulence over large inland lakes is also noticeable. Similarly the increased bumpiness when reaching hilly, wooded country after flying over flat pasture is well known. Durst^{1*} demonstrated the much greater frictional drag over land as compared with sea by examining the ratio of surface to geostrophic wind for offshore and onshore winds at Gorleston on the East Anglian coast. His results are summarized diagrammatically in Figures 8 and 9 of Chapter 13 (Wind). All these characteristics of turbulence within the friction layer are intuitively obvious and are readily exploited in flight forecasting.

If there is a sufficiently brisk wind to maintain a well stirred friction layer the lapse rate tends to become adiabatic. The lapse rate is also influenced by other factors such as the previous history of the air mass, the temperature of the underlying surface, etc. and generally speaking the steeper the lapse rate the more readily do vertical gusts develop and thus the more vigorous the turbulence. Conversely if the other factors operate to encourage great stability, vertical motion tends to be suppressed and turbulence is accordingly heavily damped. Thermal turbulence over land is thus subject to a marked diurnal variation with a maximum by day and a minimum at night.

Vertical gusts associated with turbulence are directed downwards as well as upwards and this explains the strongest gusts evident on a record of the horizontal wind speed; these arise when air is brought down to the surface from some height where the horizontal speed is greater than the mean speed at the surface. In this way extreme gusts may approach the geostrophic wind appropriate to the free air near the top of the friction layer.

20.2.2. Turbulence in cloud

Clouds are mostly formed as a result of adiabatic expansion leading to cooling and subsequently to condensation of water vapour. The adiabatic expansion is almost invariably due to ascent of the air and so vertical motion is a normal

*The superscript figures refer to the bibliography at the end of this chapter.

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feature of clouds. The vertical motion may be the gentle ascent on a scale of many hundreds of miles associated with synoptic systems such as fronts and depressions; it may be on a scale of up to five miles or so in the case of thermal convection; or it may be on a much smaller scale, say a few hundred feet, when mechanical turbulence (forced convection) is operating. There is, however, no clear-cut division between these scales of motion and they may often all occur simultaneously. For example, convective up-draughts may be embedded within the extensive cloud mass of a cold front and small-scale gusts may also be superposed on these motions. Even in the absence of general air-mass instability, the patchiness or heterogeneity of the atmosphere as regards both temperature and humidity gives rise to localized instabilities in most clouds, however formed. We see then that all clouds are inseparably associated with vertical motions and are liable to be turbulent to some degree. Thus even the most innocuous cloud, for example a patch of altocumulus, is liable to produce a little bumpiness in an aircraft passing through it. Undoubtedly, however, convective clouds form the most important source of bumpiness in aircraft.

20.2.2.1. *Stratocumulus*. Much of the stratocumulus cloud which occurs in temperate latitudes, especially in winter, is formed and maintained by frictional turbulence. The vertical exchanges of air associated with the frictional eddies result in a thoroughly mixed surface layer and if this extends beyond the condensation level a layer of stratocumulus forms in the upper part of the friction layer. Such cloud is merely a visible manifestation of the vertical motions which occur in the friction layer and slight or moderate turbulence within it is usual. On the rare occasions when it is severe this is either because the cloud arises from the passage of very strong winds over particularly rugged country or because instability is involved. Stratocumulus layers at higher levels, that is, those which do not owe their existence to surface friction, are also usually turbulent to some degree, as illustrated by Figure 1 showing sections of accelerometer traces obtained by aircraft of the Meteorological Research Flight near stratocumulus cloud.

A well marked inversion near the cloud top is a normal feature of such cloud layers and an interesting aspect of these results obtained by James² is that the turbulence extends to about 200 feet above cloud top. Quite smooth flying is usually to be found upwards of about 300 feet above cloud top.

20.2.2.2. *Convective cloud*. Convective clouds always contain vertical motions on a scale appropriate for the production of bumpiness. However, clouds of this genus range from small fair-weather cumulus having a depth of a few hundred feet up to the mighty cumulonimbus of the tropics and subtropical continents having a depth of many tens of thousands of feet. Accordingly, the intensity of turbulence in convective clouds ranges from the trivial to the very severe. In general the size of the cloud is a good guide to the degree of turbulence likely to be found within it. As a result of recent investigations into the convective process by Ludlam³, Scorer⁴, Malkus⁵, Saunders⁶, Woodward⁷, and many others, the theory of convection has been extended considerably. A descriptive account of the process as currently regarded is given in Chapter 16 (Clouds and precipitation). Essentially the motion within a thermal is believed to be similar to a vortex ring with the air in the centre rising faster, relative to the motion of the bubble as a whole, than the peripheral air. As a result of entrainment at the sides and rear the bubble becomes enlarged and diluted during its rise. Similar motions continue in the cumulus cloud which forms above the condensation level, although here the

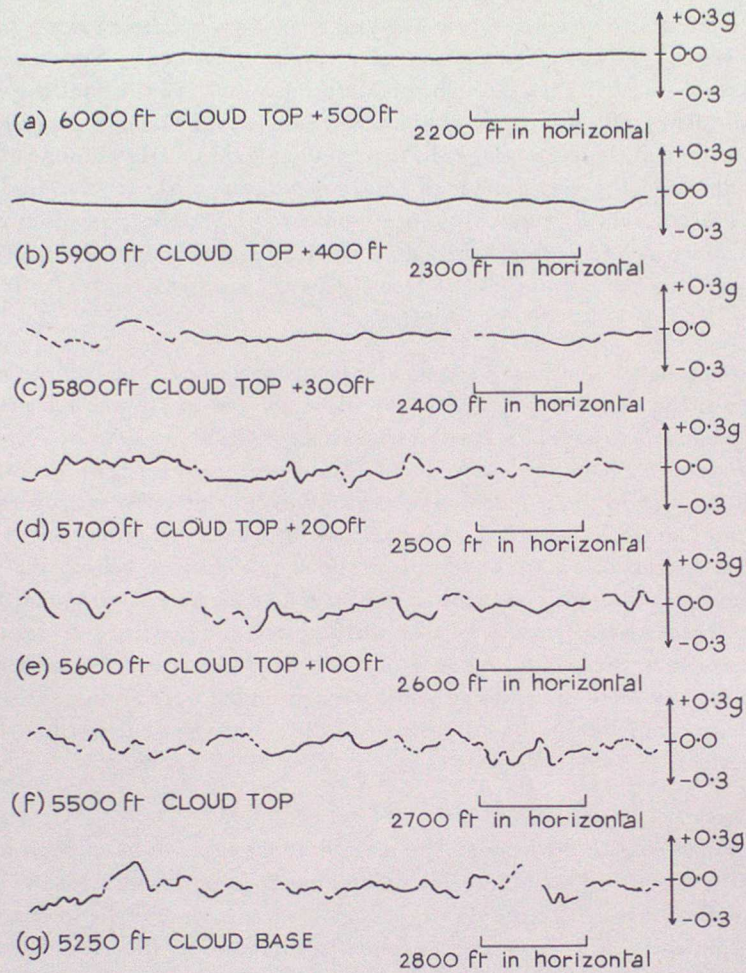
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FIGURE 20.1 Accelerometer records obtained near stratocumulus cloud, 14 November 1955 (after James²)

buoyancy may be considerably augmented by the latent heat released in the condensation process. Accordingly much more powerful vertical currents are found within convective clouds than in the thermal currents below cloud base.

In very large cumulus and cumulonimbus there may be several convective cells each behaving more or less independently of neighbouring cells and having an independent life history of perhaps a few hours. The life history, described in detail in Chapter 16 (Clouds and precipitation), includes three stages usually described as building, mature and dissipating. During the first stage a general up-draught prevails and in the largest and most violent storms peak upward velocities of 100 ft sec^{-1} are known to occur occasionally. During the mature stage which includes the onset of precipitation, part of the up-draught becomes replaced by a down-draught which may attain 40 ft sec^{-1} in extreme cases. During the dissipating stage extensive but more gentle down-draughts predominate.

In the context of bumpiness in aircraft American authors have drawn a distinction between the sustained up- and down-draughts in large convective clouds and the gusts of local and transitory character. It is argued that the main

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draughts form part of an organized system on a scale of up to a few miles, whilst the gusts, having a scale of up to a few hundred feet, may occur anywhere in the system. R.F. Jones⁸, however, has produced convincing evidence from a series of carefully instrumented flights through thunderstorms that it is in fact the entry into the main draughts which is most productive of the severe bumps experienced by an aircraft, rather than the passage through random gusts. His point is that although the main draughts may appear to have too large a scale for the production of bumpiness, the gradient of vertical velocity near their periphery is often concentrated within a few hundred feet of horizontal traverse and this is quite sufficient to produce severe bumps.

The strongest draughts and gusts in cumulonimbus are to be found in the middle and upper parts of the cloud and typically the pilot obliged to fly through such clouds is recommended to select a level as low as possible consistent with other considerations (terrain clearance, icing etc.). However, many modern aircraft are able to fly high enough to clear cumulonimbus tops except perhaps in tropical regions. The accelerations imposed on an aircraft by gusts are proportional to the speed of the aircraft and a reduction of airspeed is therefore beneficial during flight through turbulent conditions. Too much reduction of airspeed, however, may expose the aircraft to the risk of stalling due to temporary disappearance of the wing lift in the gusts. Choice of the best flight speed for such conditions must therefore be a compromise and a recommended safe flying speed for flight in turbulent conditions is usually given in the Flight Manual for the particular aircraft.

Height changes during flight through the main draught regions have been known to exceed 2000 feet (rare in temperate latitudes) but it is preferable for the pilot not to resist such changes. Diving down through a strong up-draught in order to preserve the flight altitude causes the airspeed to increase so that accelerations produced by gusts are more violent; climbing through a down-draught reduces airspeed and increases the risk of stalling. The extreme vertical gust measured during the United States Thunderstorm Project⁹ amounted to 75 ft sec^{-1} , sufficient to produce accelerations of $2g$ to $3g$ in typical transport aircraft.

There is no reason to suppose that severe gusts of similar magnitude do not occur also in Europe, albeit more rarely. Jones¹⁰ concluded, from a comparison of results obtained over England with those over Florida, that bumps of $0.6g$ or larger are more frequent over Florida than over England but bumps of less than $0.6g$ are more frequent over England. The frequency of occurrence of bumps of $0.4g$ is about the same in both areas, namely, one per 2000 yards of cumulonimbus flying. As most pilots regard bumps of $0.4g$ as severe, it is reasonable to state that moderate to severe turbulence is more frequent in cumulonimbus over England than over the United States but this is not true of the extremely severe but much more rare bumps.

In dealing with convection the operational forecaster is mostly obliged to restrict himself to the "parcel method" when examining tephigrams. In so doing the net positive area between the ascent curve for the parcel and the environment curve is a good guide to the vigour of convective clouds. J.J. George¹¹ recommends use of the maximum temperature difference between the parcel and environment curves on the following basis:

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TABLE I *Intensity of turbulence in terms of maximum temperature difference (ΔT) up to 400 millibars between parcel and environment curves (after J.J. George)*

$\Delta T(^{\circ}\text{C})$	<i>Turbulence</i>
0 to 3	light
4 to 6	moderate
7 to 9	severe
over 9	extreme

Undoubtedly, however, the total vertical extent of the convection cloud is also a relevant factor. Clearly there is more opportunity for strong vertical currents to become developed if the instability is not only great but is released over a deep layer. Convection in considerable depth and pronounced instability both imply marked turbulence and if both apply simultaneously the forecaster is well advised to indicate the liability to severe turbulence.

With the spread in the use of meteorological radar equipment for the surveillance of precipitation and the increasing use of airborne radar equipment, it is appropriate to remark here that radar can be of considerable value in the detection of clouds productive of turbulence. The radar echo given by a cumulonimbus has definite characteristics which are easily recognized with experience. The echoes have high intensity with sharply defined edges and tops when the cloud is in the developing stage, but become diffuse when the cloud has passed its maximum development. Jones¹⁰ examined in some detail the relation between turbulence as encountered during a series of special flights through cumulonimbus and the simultaneous echoes seen on ground-based radar equipment. He found that the vast majority of severe gusts were encountered in clouds from which a radar echo with sharply defined edges was received. Thus only one of 44 gusts of $\pm 0.8g$ or greater was associated with a cloud giving a generally diffuse echo. It was clear, too, that the region of a cloud corresponding to the edges of the echo was a preferred region for bumps, especially the more severe ones, with upward bumps predominating where the echo-producing region of the cloud was entered and downward bumps where the echo-producing region was left. The results suggest that the well marked echoes from cumulonimbus clouds arise from the main draught regions and support Jones's thesis that the most severe bumps occur where the horizontal gradient of vertical velocity is at a maximum, namely, around the periphery of the main draughts. Clearly radar can be a valuable aid to the avoidance of severe turbulence especially at night, or when cumulonimbus may be embedded within other more general cloud.

20.2.3. *Turbulence at fronts*

Fronts, being regions where the wind and wind shear are commonly strong and where thick cloud is often present in depth, are potentially turbulent. Cold fronts are usually narrow, the active zone being typically about 20 miles wide whilst warm fronts have widths of the order 100 to 200 miles. Cold fronts in general have a good deal of cumuliform cloud, including cumulonimbus, embedded within the frontal cloud. Warm fronts more usually comprise layered cloud systems, but occasionally the cloud may assume instability form when the warm air mass being lifted at the front is convectively unstable.

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In assessing the likelihood of turbulence in a frontal zone, the forecaster will be guided by the general wind strength and the intensity of wind shear, together with all available indications of the activity of the front including of course the relevant tephigrams. It is not easy, however, to assess frontal activity from synoptic parameters owing to the complexity and limited understanding of the dynamics of fronts, and nothing is as useful to the forecaster as specific observations of cloud structure and precipitation. Generally speaking an active front from the point of view of cloud and weather will also be active from the point of view of turbulence, especially if instability is involved. However, the upper parts of fronts may also be turbulent even in the absence of cloud.

20.2.4. Turbulence over hills and mountains

It is well known that the air flow over hills and mountains is commonly more disturbed than over level country. Often the air flow is deformed in a systematic fashion and an organized pattern of gravity waves occurs. These waves, known as lee waves or mountain waves, have been thoroughly investigated over the past two decades or so. For information about them the reader is referred to the Meteorological Office publication *Air flow over mountains (notes for forecasters and pilots)*¹² also to World Meteorological Organization *Technical Notes No.18*¹³ and *No.34*¹⁴. In the present section of this chapter the discussion will be confined to the occurrence of turbulence over mountains.

20.2.4.1. Turbulence in the friction layer over mountains. Over irregular mountainous terrain the friction layer is usually more variable in depth than over level country. The irregularities of the terrain cause the air flow to separate from the surface and lee eddies form here and there, so that many of the terrain irregularities are filled in by some form of turbulent wake. As one would expect, therefore, turbulence within the friction layer is likely to be more vigorous over mountains than elsewhere.

The existence of such turbulence is often indicated by the form of stratocumulus cloud. Where a substantial and lengthy lee slope exists in a region of very large mountains (for example the Sierra Nevada in the Rockies), the turbulence may be rendered spectacularly visible by the cloud-fall (föhn wall) sweeping down the lee slope. Kuettner¹⁵ regards the proper control of an aircraft in this turbulent region as virtually impossible and recommends that flight in this zone should always be avoided. However, apart from the serious dangers which arise in special locations amongst the highest mountain ranges of the world, pilots are often obliged to fly at times within the friction layer above moderate-sized hills and mountains. In such circumstances, the factors which determine the degree of turbulence are the same as those which are relevant over level country, namely, wind strength, static stability and surface roughness. Other things being equal, and as turbulence forecasting for aviation is highly subjective and only qualitative, the forecaster can best deal with this by predicting turbulence in the friction layer over high ground to one degree higher on the descriptive scale than is expected over level country unless he has definite evidence to the contrary such as aircraft reports. For example, if in a strong unstable airstream moderate turbulence is expected generally in the friction layer and in cumulus cloud, the forecaster may add, appropriately, "but locally severe over high ground". If severe turbulence is being forecast generally, he might add "especially over high ground".

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The phenomenon called by Förchtgott¹⁶ "rotor streaming" and described and illustrated in Chapter 13, (Wind), Section 13.6.4. can be regarded as a severe but semi-organized kind of mechanical turbulence which arises in the friction layer when an airstream of limited depth crosses mountainous country. The requirements appear to be high static stability of the air mass as a whole, that is above the turbulent layer, and strong winds confined to a limited layer no more than about $1\frac{1}{2}$ times the height of the hill.

Förchtgott's work contains some well documented cases of this particular variety of turbulence but there are few similar observations from elsewhere possibly because suitable airstreams are rare in other regions. However, Šmether¹⁷ has published some interesting results illustrating the distribution of turbulence found from special flights over mountainous areas of the U.S.S.R. He found that in general the worst turbulence occurred immediately above a mountain and over the lee slopes, with a zone of less severe turbulence extending banner — fashion in the downwind direction. Šmether's results for a particular occasion over the Suramskij Pass are reproduced as Figure 20.2.

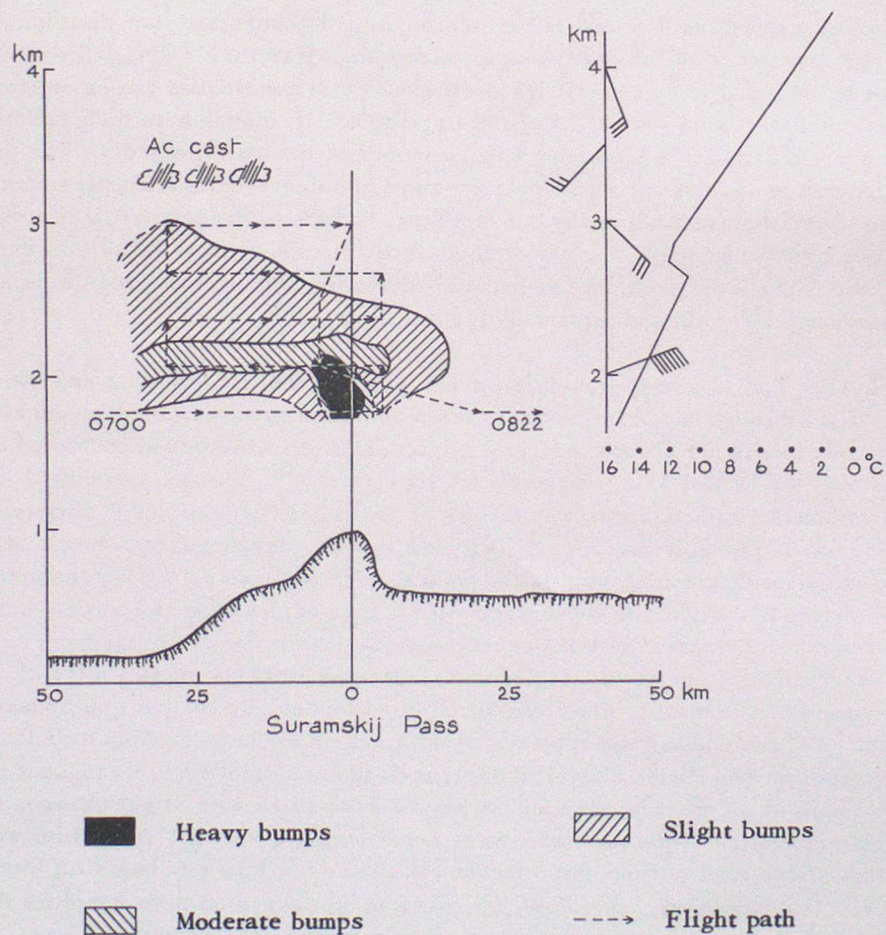


FIGURE 20.2 Structure of the bumpy zone over the Suramskij Pass during the flight of 22 August 1955, 0610 hr to 0926 hr. [Upper winds and temperatures are given at right of diagram, and each full feather represents 4 kt]. (after Šmether¹⁷).

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20.2.4.2. *Turbulence in the rotor zone.* Förlch's "rotor streaming" is not to be confused with the rotor or roll cloud zone which often forms an important part of the wave flow over moderate and large mountains. Such zones comprise something akin to large standing eddies and lie beneath the crests of lee waves, the most powerful rotor being that beneath the first lee-wave crest downwind of the mountain ridge. The rotor zone gives rise to the most severe turbulence to be found in the air flow over mountains and on occasions may be more violent than that occurring in the worst thunderstorms. During the Sierra Wave Project¹⁸, many traverses were made near and under the rotor zone while aero-towing gliders. Vertical accelerations of 2g to 4g were common and 7g was exceeded on one occasion. On another occasion one of the project gliders disintegrated and the pilot narrowly escaped with his life.

Away from the Sierra Nevada and other locations amongst very high mountains productive of powerful effects, the rotor zone manifests itself in a less violent form. Certainly, for example, roll clouds are observed from time to time to the lee of Alpine ranges and from such evidence as is available accelerations of 2g to 4g may occur. The "Helm" bar of Crossfell in Cumberland is another example of a rotor or roll cloud zone which forms occasionally in strong easterly airstreams.

The forecasting of roll cloud zones in any detail is essentially specialized and requires experience of the particular local terrain. Accordingly detailed predictions cannot be included in everyday flight forecasting. The most that can be expected of the forecaster is an indication of the liability to roll clouds with their severe turbulence in favourable locations which cannot be specified precisely. The pilot's best insurance against encountering rotor zone turbulence is an adequate height margin above the mountain peaks. If there are reasons to expect strong effects, for example from the forecast, the appearance of the clouds, or from the pilot's experience, the flight level should be at least $1\frac{1}{2}$ times the height of the mountains above the surrounding terrain and preferably higher.

20.2.4.3. *Turbulence in mountain waves.* Outside the friction layer and the rotor zone, flight through mountain waves is often characterized by marked smoothness. This, however, is not always the case. In 66 examples of waves encountered by pilots over the British Isles and analysed by Pilsbury¹⁹, 20 were associated with some turbulence although this was mainly of the slight "cobble-stone" variety. The explanation is probably that intensified wind shear is developed as a result of the perturbations of horizontal wind in the waves. Gerbier²⁰ noted similar turbulence in waves during his studies in the French Alps. This explanation is scarcely adequate to account for the severe turbulence associated with waves which has been reported from other parts of the world. For example, over the Rockies smooth wave clouds have sometimes been observed to assume, quite suddenly, a ragged torn appearance indicative of the sudden breakdown of smooth wave flow into vigorous turbulence. It appears that sometimes this breakdown operates simultaneously throughout the entire depth of the wave system and it may be associated with slight changes in the characteristics of the airstream when conditions are near the critical for waves to occur. Such explanations are speculative and do not form any basis for forecasting. It is necessary, therefore, for pilots to be always on their guard for the sudden onset of turbulence during flight through waves over mountains.

20.2.5. *Clear-air turbulence*

20.2.5.1. *General.* Turbulence arising from the frictional drag at the earth's surface and from free convection is familiar and readily understood in a general

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way. Thus the onset of bumpiness during flight in the lowest few thousand feet or in cumuliform cloud at any height comes as no surprise. However, the operation of aircraft in the immediate post-war years at ever increasing heights soon revealed that bumpy conditions were sometimes to be found in clear air in the upper troposphere and lower stratosphere, namely, in regions where in the absence of cloud it had been expected that quite smooth flying conditions would obtain.

The evidence now accumulated indicates that clear-air turbulence is distributed from 20,000 to 40,000 feet with a marked tendency for a maximum incidence near jet streams and the tropopause. The frequency falls off rapidly in the stratosphere. The turbulence is commonly limited to shallow layers less than 500 feet thick and is often of limited horizontal extent. The intensity is usually slight or moderate and only occasionally severe. On the whole it is a fairly rare phenomenon as evidenced by the difficulty encountered during some investigations in finding instances of clear-air turbulence for study.

20.2.5.2. *Observational evidence of clear-air turbulence.* There are some reports on record of very severe gusts occurring in clear air. Hislop²¹ for example describes an incident to a Comet aircraft when accelerations of 2.0g and -2.6g were recorded. Bindon²² reports a case over Canada when the peak acceleration reached 3g. Although other such extreme incidents have been reported they are quite rare and the evidence now accumulated indicates that if clear-air turbulence occurs at all it is most likely to be only slight or moderate.

There have been numerous analyses of reports of clear-air turbulence obtained either in the course of regular transport flights or from sorties specially flown for the investigation of turbulence. One characteristic found by most investigators has been the quite limited extent of turbulent layers both in the horizontal and in the vertical. For example, the horizontal extent has been variously reported as ranging from less than 10 miles (for example Coleman and Funk²³) up to 90 miles (for example Hislop²⁴), whilst the vertical extent has been quoted as 500 feet (Clem²⁵) to 3000 feet (Clodman²⁶). The picture that emerges from these studies is one of shallow turbulent layers often having a depth of only a few hundred feet and having meso-scale horizontal dimensions. According to Reiter²⁷ the horizontal distribution sometimes takes the form of bands orientated parallel to the wind. From the pilot's point of view, escape from clear-air turbulence will often be available to him by a change of level.

During the United States high-altitude gust research programme, accelerometers descended by parachute after being carried aloft by balloon, and the accelerations encountered were telemetered to the ground. An average of rather more than two turbulent layers per sounding (mostly reaching about 60,000 feet) was found, with the maximum frequency of thickness occurring at about 500 feet. These results confirm those derived from aircraft reports but in other respects there were inconsistencies, probably owing to the totally different nature of a balloon-borne gust sonde as a device for sensing turbulence.

Bannon^{28,29} analysed aircraft reports of turbulence arising from many sources during the immediate post-war years and was the first to establish an association between clear-air turbulence and the jet stream, which has since been confirmed in a number of other investigations. Bannon's diagram²⁹ is reproduced as Figure 20.3, and illustrates elegantly the distribution of reports of severe turbulence relative to the jet axis. The reports plotted are either subjective reports of

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severe turbulence or, when instrumental readings were available, of accelerations $\geq 0.4g$, experience having shown that most pilots regard bumps of $0.4g$ or more as severe. The plotting of the reports on one common diagram was made possible by using pressure relative to the jet axis as the vertical co-ordinate and the distance from the axis to the point on the low-pressure side where the wind speed fell to half the maximum, as the horizontal unit of distance.

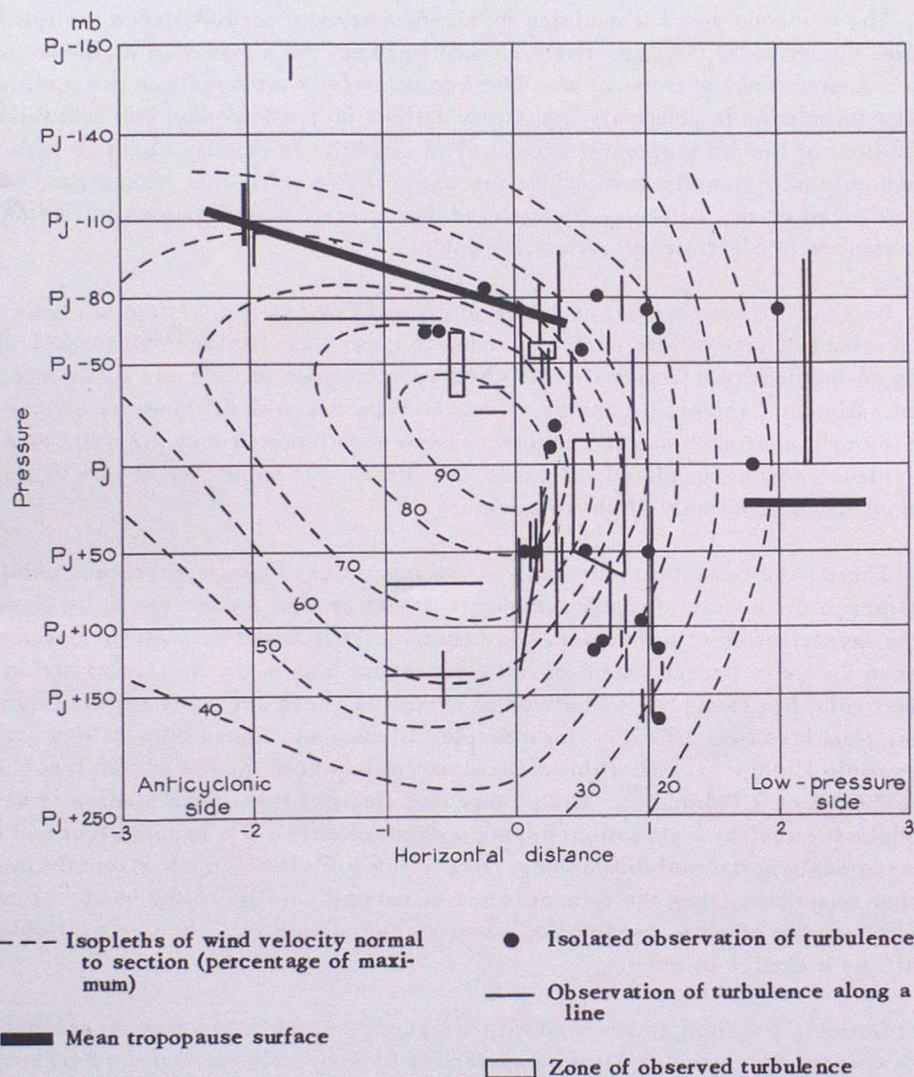


FIGURE 20.3 Positions of occurrences of severe turbulence relative to the jet-stream axis (after Bannon²⁹)

The cross-section of the jet stream is drawn from the mean of three typical jet streams. P_j is the pressure at the axis of the jet (for the three jet streams $P_j = 287$ mb). The unit of horizontal distance is the distance on the low-pressure side of the jet axis in which the wind speed falls to half its maximum value (for the three jet streams, 106 nautical miles).

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The striking feature of the diagram is the rarity of clear-air turbulence in the quadrant on the anticyclonic side of the jet below the axis. The bulk of the incidents occurred near the jet axis on the low-pressure side, although there were also quite a number above the axis on the anticyclonic side. It is clear that the regions most prone to turbulence are those where the shear, either vertical or horizontal, is greatest.

Later analyses of turbulence reports, for example by Jones³⁰ and Murray³¹ clearly confirmed that most occurrences were in the vicinity of jet streams, with an abundance concentrated on the cyclonic side. The results obtained in the American high-altitude gust research programme³² and by Brundige³³ also confirmed the low-pressure side of jets as a preferred location for turbulence.

Estoque³⁴ examined incidences of turbulence as reported in studies from various parts of the world and classified them according as whether they occurred near or remote from jet streams. His results are illustrated in the diagram reproduced as Figure 20.4.

Although the general lapse rate in the upper troposphere is more often than not somewhere between the wet- and dry-adiabatic rates, there is commonly a good deal of fine structure superimposed on the general lapse especially near jet streams. The structure often takes the form of shallow stable layers sandwiched between shallow neutral (near adiabatic) layers, with the vertical wind profile also exhibiting a fine structure with locally large vertical wind shears.

When it has been possible for occurrences of clear-air turbulence to be studied in relation to such detail it has been found that the turbulence is frequently seated within the shallow stable layers. This could be because the maxima of wind shear in the fine structure occur in those layers. Alternatively, it must be remembered that internal gravity waves attain their maximum amplitude within stable layers and some authors (for example Reiter²⁷) believe that gravity waves of short wavelength account for some of the turbulence in the upper troposphere. There is certainly some evidence, albeit limited, that high-level clear-air turbulence is more common over

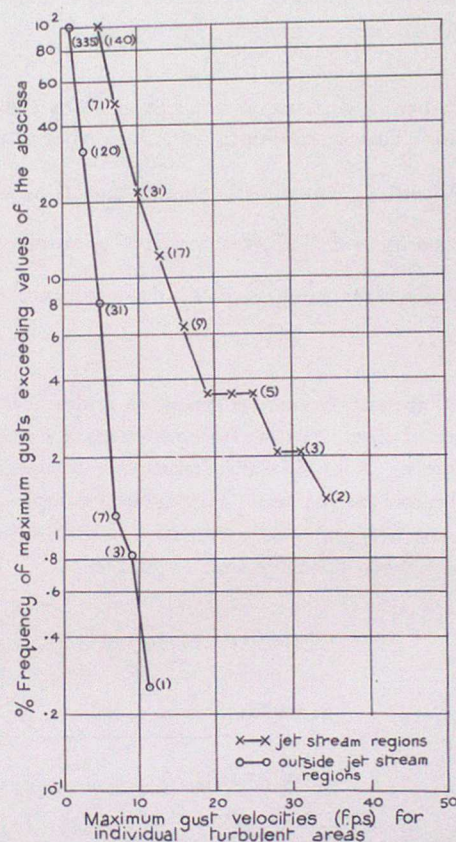


FIGURE 20.4 Cumulative frequency distribution of maximum gust velocities of individual clear-air turbulent areas.

[Numbers in parentheses indicate number of cases observed]

(after Estoque³⁴)

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mountains than elsewhere but gravity waves at such levels may not necessarily be directly associated with high ground.

20.2.5.3. *Some theoretical considerations of clear-air turbulence.* As it does not yet provide a basis for forecasting clear-air turbulence with anything approaching precision, theory receives only brief attention in this section. This disappointing progress may be because turbulence favouring bumpiness in aircraft has a very much smaller scale than can be resolved by routine meteorological data. At any rate attempts to correlate clear-air turbulence with meteorological parameters have had quite limited success.

Many workers have attempted to establish relations with parameters of the wind field. Thus a tendency for clear-air turbulence to be associated with large values of V and $\frac{\partial V}{\partial z}$ has been demonstrated in many papers, whilst according to Reiter²⁷ the parameter $V \frac{\partial V}{\partial z}$, the vertical gradient of kinetic energy, is also relevant. Other authors have suggested that the curvature of the vertical wind profile $\frac{\partial^2 V}{\partial z^2}$ is important.

Of these the best relation is undoubtedly that with the vertical wind shear, but none of these parameters provides a decisive relationship or indeed one sufficiently strong to enable the forecaster to distinguish reliably between turbulent and non-turbulent airstreams. A typical example of the relation with vertical wind shear, due to Briggs³⁵, is given in Table II, which is based on 269 pilot's reports of turbulence, both positive and negative.

TABLE II *Turbulence intensity in terms of vertical wind shear*

$\partial V / \partial z$	Nil	Slight	Moderate	Totals
<i>kt/km</i>	<i>number of cases</i>			
>20	44 (54)	9 (9)	22 (12)	75
11 to 20	64 (61)	7 (10)	14 (14)	85
0 to 10	86 (78)	15 (13)	8 (18)	109
Totals	194	31	44	269

Figures in brackets are based on null hypothesis, i.e. no relation.

Chi - squared test indicates significance better
than 1 per cent.

Bannon²⁸ sought a relation between turbulence and the Richardson number and in common with several other authors found an unmistakeable but rather diffuse relation. Bannon's results are conveniently summarized in Table III, which compares the percentage frequencies of bumpiness for various ranges of values of Ri with the percentage distribution of Ri in the mean at Larkhill.

*Bumpiness in Aircraft*TABLE III *Ratio of percentage frequencies, bumpy occasions to normal, for various ranges of $\log_{10} Ri$ (after Bannon²⁸)*

	$\log_{10} Ri$								
	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0
	to -0.5	to 0.0	to 0.5	to 1.0	to 1.5	to 2.0	to 2.5	to 3.0	and above
Upper troposphere	4.3	4.4	1.8	1.0	0.84	0.36	0.66	0.74	4.5
Lower stratosphere	-	0.0	1.1	1.4	1.1	0.62	1.0	0.41	5.0

It is clear, for the upper troposphere, that there is a much greater tendency for turbulence to arise with low Richardson numbers, < 1 (the Ri scale on the table is logarithmic), but no similar relation emerges for the lower stratosphere. The diffuseness of the relation may be due to the difficulty of evaluating Ri with sufficient accuracy on the appropriate scale or because other factors, for example horizontal wind shear, play a part. Other authors obtained similar results but in no case did a well defined limiting value of Ri emerge suitable for exploitation in practical forecasting. Sasaki³⁶ obtained rather better correlations by extending the Richardson criterion to allow for the curvature of both the wind and temperature profiles but these quantities are not easily evaluated from routine soundings.

The possible effect of horizontal shear has naturally also received attention. For example, Bannon²⁸ in one of his earlier studies evaluated the horizontal wind shear for a number of reports of bumpiness and compared the percentage frequencies of various values of the shear with the normal frequencies of those shears. His results, summarized in Table IV, show a well marked tendency for a greater liability to bumpiness with moderate to large shears than with slight shear.

TABLE IV *Ratio of percentage frequencies, bumpy occasions to normal, for various horizontal shears (after Bannon²⁸)*

	Horizontal shear (hr^{-1})								
	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
	to 0.05	to 0.10	to 0.15	to 0.20	to 0.25	to 0.30	to 0.35	to 0.40	and above
Upper troposphere	0.29	0.69	1.4	2.4	4.2	6.0	3.1	1.1	4.5
Lower stratosphere		0.57		2.2		2.9		1.0	∞

Once again other workers have obtained similar results and generally speaking the degree of dependence on horizontal shear appears about as strong as on the Richardson number. Indeed it is clear that both are relevant and are probably themselves correlated, for strong horizontal shear is usually accompanied by strong vertical shear.

The failure of theory to provide a satisfactory explanation of clear-air turbulence may not necessarily be due to shortcomings of the theory itself. Radio-sonde data

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at 12-hour intervals from stations hundreds of miles apart cannot possibly provide sufficiently accurate values of the parameters appropriate to a phenomenon which is patently transient and of small scale.

20.3 THE RESPONSE OF AIRCRAFT TO TURBULENCE

If we consider various surface vehicles such as lorries, cars, bicycles, and even roller skates, it is clear that when travelling over the same uneven surface the pattern of bumps imparted to their users will be quite different. This is of course due to the wide differences in their size, speed, suspension characteristics, etc. They necessarily act selectively in their response to the irregularities of the road. It is not always fully realized by meteorologists that similar considerations apply to the behaviour of different types of aircraft flying through turbulent air, and it is necessary to draw a clear distinction between turbulence and bumpiness. Turbulence relates to eddies in the flow of the atmosphere and bumpiness to what is felt within an aircraft. For example the effect of small-scale eddies in a large, fast, heavy aircraft might well be negligible but might result in marked bumpiness in a small, slow, light aircraft. These differences in the response of aircraft to turbulence depend in a complicated way upon the aerodynamic characteristics of the aircraft, but before discussing this a little further it is profitable to consider the effect of an isolated gust rather than a complete spectrum of turbulence. This has been discussed by Parker³⁷, who computed the effect of gusts, both vertical and horizontal, on various types of aircraft.

If an aircraft encounters a "sharp-edged" gust (vertical), namely, one which grows to its maximum value in zero horizontal distance, the lift on the wings is instantaneously increased or decreased and an acceleration is imparted to the aircraft. The magnitude of this acceleration can be computed given certain facts about the aircraft. The effect of the gust amounts to a sudden change in the angle of incidence of the wings to the direction of the air flow. A sudden horizontal gust also modifies the wing lift and the vertical acceleration produced by such a gust can similarly be computed.

In practice sharp-edged gusts do not occur and the gusts grow to their maximum value over some finite distance. The "equivalent" or "effective" gust is one in which the vertical velocity grows linearly to its maximum over a horizontal distance of 100 feet. The acceleration imparted to an aircraft by a specified effective gust is of course less than that produced by a sharp-edged gust of the same magnitude. The reduction in acceleration is determined by a factor called the "alleviation" factor, the value of which depends on the aircraft parameters in a complicated manner. Parker's results for the accelerations imparted to three aircraft types by horizontal and vertical gusts are reproduced in Table V.

TABLE V *Vertical accelerations produced on different aircraft by certain gusts (after Parker³⁷).*

Aircraft type	Vertical sharp-edged gust of 25 ft/sec E.A.S.*	Horizontal sharp-edged gust of 25 ft/sec E.A.S.*	Vertical gust growing linearly to 25 ft/sec in 100 ft
Comet I	1.11 g	0.14 g	0.91 g
Constellation	0.62 g	0.14 g	0.53 g
Slow small aircraft	2.05 g	0.37 g	0.94 g

*Equivalent airspeed = true speed of gust $\times \sqrt{\rho/\rho_0}$, ρ being density, ρ_0 the M.S.L. value.

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The table shows striking differences in the response of these three aircraft to vertical sharp-edged gusts, the effect on the Constellation being about half that on the Comet I, and on the light aircraft about twice. These differences are however reduced when an effective gust reaching the same magnitude is considered. Another point is that horizontal gusts are far less effective than vertical gusts in producing vertical accelerations and this characteristic is generally true for conventional aircraft. Thus the response of the Comet I to a horizontal sharp-edged gust is only about one-eighth of that due to a vertical sharp-edged gust of the same magnitude.

In the free atmosphere turbulence takes the form of a continuous spectrum of gusts arising from three-dimensional eddy motions having eddy sizes ranging from the minute to thousands of miles, the latter scale representing the disturbances seen on synoptic charts. Roughly speaking bumpiness in aircraft arises from those eddies within the scale range of 50 to 500 feet, although very small slow aircraft would be affected by somewhat smaller eddies and very large high-speed aircraft by even larger eddies. When flying through turbulent air an aircraft responds to the spectrum of gusts and a spectrum of accelerations is imposed on the aircraft, the accelerations being felt as bumpiness by the occupants. The response of the aircraft is, however, by no means the same at all frequencies. Indeed there are usually some eddy sizes to which an aircraft is particularly sensitive and others which have less effect. The sensitivity occurs at those frequencies near the natural modes of vibration of the aircraft when in normal flight. This effect can be very marked in some aircraft and the response near a particular frequency may be an order of magnitude greater than at other frequencies within the effective range. As an example, the Canberra aircraft is especially sensitive to disturbances imposed at a frequency of about six cycles per second and for this reason most turbulence results in "cobble-stone" bumpiness at about this frequency in this particular aircraft. Other aircraft behave differently and it is important to realize that the trace produced by a recording accelerometer carried within an aircraft does not indicate directly the spectrum of turbulence in the atmosphere. It indicates the response of the particular aircraft to the current state of turbulence, with the amplitude at some frequencies partially suppressed and considerably amplified at others.

These aspects of the effect of turbulence on aircraft may be formalized and treated mathematically by the techniques of power spectrum analysis. The reader wishing to pursue the matter is referred to Panofsky³⁸, Zbrozek³⁹ and Press⁴⁰.

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